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PARTICLE CONCENTRATIONS INSIDE A TAVERN BEFORE AND AFTER PROHIBITION OF SMOKING: EVALUATING THE PERFORMANCE OF AN INDOOR AIR QUALITY MODEL

by

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Abstract

Measurements were made of respirable suspended particles (RSP) inside a sports tavern on 26 dates over approximately two years (May 17, 1992, to February 11, 1994) during which smoking was allowed. Without notice, the local city government passed a regulation prohibiting smoking in taverns, beginning May 1, 1994. Two follow-up field studies consisting of 50 visits were conducted to measure changes in RSP levels after smoking was prohibited. No decrease in tavern attendance was evident after smoking was prohibited. During the smoking period, the average RSP concentration was 56.8 $\mu g/m^3$ above the outdoor concentrations, but the average dropped abruptly to 5.9 $\mu g/m^3$ above outdoor levels -- a 90% decrease -- on 24 visits in the first two months after smoking was prohibited (first follow-up study). A second set of 26 follow-up visits (matched by time of day, day of the week, and season to the earlier smoking visits) yielded an average concentration of 12.9 $\mu g/m^3$ above the outdoor levels, or a decrease in the average RSP concentration of 77% compared with the smoking period. During the smoking period, RSP concentrations more than 100 $\mu g/m^3$ above outdoor levels occurred on 30% of the visits. During 52 nonsmoking visits, 93% of the RSP concentrations were less than 20 $\mu g/m^3$ above outdoor levels, and no concentration exceeded 100 $\mu g/m^3$ on any visit. Thus, the tavern experienced a striking decline in indoor RSP concentrations after smoking was prohibited. The indoor concentration observed in the nonsmoking periods (9.1 $\mu g/m^3$ average for all nonsmoking visits) was attributed to cooking and resuspended dust. A mathematical model based on the mass balance equation was developed that included smoking, cooking, and resuspended dust. Using cigarette emission rates from the literature, the tavern volume of 521 m^3, and the air exchange rate measured in the tavern under conditions regarded by the management as "typical", the model predicted 42.5 $\mu g/m^3$ for an average smoking count of 1.17 cigarettes, which compared favorably with the average concentration of 43.9 $\mu g/m^3$ observed in the tavern. A regression analysis indicated that the active smoking count explained over 50% of the variation of the RSP concentrations measured on different dates. The model is suggested for estimating RSP concentrations from smoking in other similar taverns under similar conditions.

PARTICLE CONCENTRATIONS INSIDE A TAVERN BEFORE AND AFTER PROHIBITION OF SMOKING: EVALUATING THE PERFORMANCE OF AN INDOOR AIR QUALITY MODEL

INTRODUCTION

Across the nation, various actions are being taken at the city, county, and state level to restrict or prohibit smoking in public locations. In California, many restaurants have voluntarily decided to prohibit smoking. Even without official prohibition, it is widely believed that smoking activity in indoor settings has been decreasing over time. As indoor smoking declines, an important question is: "In view of the low smoking activity, will air quality change inside taverns and other similar locations when smoking is prohibited altogether, and, if so, how great will this change be?" Surprisingly, little recent data are available on the concentrations in indoor settings from smoking, and virtually no data are available on the before-after effects of eliminating smoking in restaurants, taverns, bars, stores, etc.

Because some pollutants emitted by cigarettes also are generated by cooking and other sources, it can be difficult to distinguish smoking activity from other indoor sources. Ideally, one would like to conduct the following experiment: measure the concentrations in a real smoking location under normal conditions over several months, ask the smokers to stop, and then measure the levels again over several months. Recent ordinances adopted by city, county, and state levels to prohibit smoking in California provide an opportunity to conduct a "natural experiment" in bars, restaurants, stores, and other on-site locations.

In the present investigation, a crowded sports tavern -- a well-known bar and grill on El Camino Real -- was selected within one-half mile of Stanford University in Menlo Park, CA.

This sports tavern has operated since 1932 at the same location and is a popular meeting place for students, visitors, and local residents. The tavern has two large-screen television sets that allow patrons to view sporting events through cable, local stations, and satellite hookups. The tavern features salads, sandwiches, french fries, hamburgers and a variety of specialty foods cooked on its grill, as well as peanuts whose shells become strewn on the floor and fresh pizzas cooked in its ovens. The entrance door (opening to an adjacent alley) and the outdoor patio door are opened when the weather is favorable. The main part of the tavern is one large rectangular room (47 ft x 48 ft = 2,256 ft^2 or 209.6 m^2) with tables, surrounded by 8 booths without doors against two of its walls, with each booth capable of seating 4-5 persons. Attendance indoors at the tavern ranges from 10 to 75 persons, although more than 100 persons have been observed inside on rare occasions, such as major sporting events. The cooking grill is located behind a stand adjacent to a 20-ft long bar with 8 seats, but it is still part of the main room, which has a volume of 19,363 ft^3 or 548 m^3. Assuming that pillars, columns, pinball machines, and furniture, etc., account for 5% of the available volume, the resulting net mixing volume is 521 m^3.

Several reasons for selecting this tavern for detailed study were: (1) its similarity to hundreds of other sports taverns throughout the area with respect to physical size, activities available to patrons, food served, method of cooking, and drinks served; (2) its management's cooperation and approval of our study of indoor concentrations, smoking counts, customer counts, and air exchange rate measured on one date; (3) the historical smoking counts that were available from a previous study in this tavern done 14 years earlier.

Earlier studies carried out by Repace and Lowrey (1980) reported levels of Respirable Suspended Particles (RSP) in a variety of public locations (for example, a lodge hall, bar and

grill, pizzeria, bingo game, church, bowling alley, hospital waiting room, inn, shopping plaza, fast-food restaurant, sports arena, hotel bar) in Washington, DC, in March-June, 1979, using the same type of measuring instrument that was used in the present investigation. The median size (i.e., "cutpoint") of the particles they collected was 3.5 micrometers, and the indoor concentrations that they observed ranged from 55 to 697 $\mu g/m^2$. Reviews of field measurements of environmental tobacco smoke (ETS) are given in Repace (1987a) and in Guerin, Jenkins, and Tomkins (1992). Other studies of ETS in indoor settings have been conducted in chambers (Leaderer, *et al.*; 1984; Leaderer and Hammond, 1991; Lofroth, *et al.*, 1989), or in automobiles (Ott, Langan, and Switzer, 1992).

Investigators also have constructed and evaluated mathematical models designed to predict ETS in indoor settings (Brief, 1960; Bridge and Corn, 1972; Jones and Fagan, 1974; Repace and Lowrey, 1982; Rosanno and Owens, 1969; Turk, 1963). Repace (1987b) provides a literature review of the ETS indoor air quality models. Although the models allow predictions to be made of the likely RSP concentrations before and after smoking was prohibited in a public location, none of the previous studies has examined the before-and-after concentrations in a real setting such as a tavern. These events, then, offer a unique opportunity to: (a) assess the contribution of smoking to indoor air quality levels, and (b) evaluate the performance of indoor air quality models.

METHODOLOGY

The field survey consisted of visits to the tavern on a number of different dates and times of day for nearly three years (from June 17, 1992, to December 20, 1994). Our visits were

intended to simulate the visits made by ordinary patrons who come there to eat, drink, watch television, and socialize. On each visit, the investigators: (1) periodically counted the total number of persons present; (2) counted the number of cigarettes that were actively being smoked periodic intervals; (3) measured successive RSP concentrations over the entire visit; and (4) measured outdoor concentrations immediately before and immediately after each visit. To make the counts of customers and active smokers, an investigator walked throughout the tavern approximately every 7 minutes, looked into every booth, and noted on a clip board the counts of active smokers and attendees.

Prior to entering the tavern, the investigators made several RSP measurements outside the tavern before each visit; at the end of each visit, they made another set of similar outdoor measurements. When they were inside the tavern, the investigators placed the monitor during every visit at the he same location on a central table. The monitor measures continuously, and average readings were taken approximately every two minutes, giving a sequence of 2-minute average concentration readings over the entire visit. In summary, each visit collected: (a) outdoor measurements before entering the tavern, (b) a sequence of indoor readings inside the tavern (during visits lasting from 10 min to 2 hour and 10 minutes) along with (c) periodic customer and active smoking counts, and (d) outdoor measurements after leaving the tavern.

Measurement Method

All RSP measurements were made with the Model 8510 piezobalance (Thermo-Systems Inc. or TSI; St. Paul, MN). The piezobalance is a portable instrument designed to measure the mass concentration of particles using a piezoelectric micro-balance sensor (Sem and

Tsurubayashi, 1975). The instrument has a long history of applications to the measurement of cigarette smoke in indoor settings. It was originally designed to monitor RSP levels in occupied buildings in Japan, because Japanese law requires measurements of RSP levels several times each day in stores, offices, apartment buildings, and other buildings. Japan has adopted a law limiting the allowable concentration of airborne particles smaller than 10 micrometers not to exceed 150 $\mu g/m^3$ in buildings greater than 3,000 m^2, and tobacco smoke is the primary violator (Sem and Tsurubayasyi, 1975).

A piezoelectric microbalance consists of a disk of crystalline quartz, about 0.2 mm thick and 13 mm in diameter. Thin metal electrodes are sputtered onto the opposing sides of the disk. The crystal can be made to oscillate at a highly stable resonant frequency in an electric circuit. As particle mass sticks to the oscillating (electrode) region, the resonant frequency decreases in direct proportion to the mass of the adhering material. Under highly controlled conditions, a mass as small as 10^{-11} g can be sensed. In actual field monitoring instruments, a sensitivity of about 10^{-9} is readily achieved.

Olin and Sem (1971) derived a linear equation for the aerosol mass concentration and the change in crystal operating frequency for a crystal of the type used in the TSI Model 8510 piezobalance. The equation includes a factor that accounts for the aerosol sample flow rate, crystal mass sensitivity, and aerosol collection sensing efficiency. Further theoretical details of the measurement method are discussed in Daley (1974), Daley and Lundgren (1975), Olin , Sem and Christenson (1971), and Carpernter and Brenchly (1972). Daley and Lundgren (1975) have investigated the factors affecting piezobalance crystal performance: temperature effects, humidity effects, particle collection characteristics, response linearity, and mass sensitivities.

Sem and Tsurubayashi (1975) describe the first commercial version of the instrument, the Model 3200A. The air stream enters through an impactor that traps particles larger than the desired cut size. Particles smaller than the cut size pass through an exit of the impactor, then through a short transport tube to the precipitator. In the precipitator, the aerosol passes axially along the precipitator needle and through a nozzle that forces the particles through the high intensity portion of the corona discharge. The negative-polarity discharge, passing from needle tip to crystal electrode, charges the particles and the electrical field causes them to collect on the crystal sensor. The particles are deposited on a piezoelectric microbalance sensor that is oscillating at about 5 MHz. Because the nominal frequency of the sensor is 5 MHz, the measured frequency is reduced to a more convenient range (several kHz) by electronically subtracting the sensor frequency from a slightly higher, stable reference frequency. The resolution of the counter is $\pm$ 1 Hz, which corresponds to a mass loading on the sensor of approximately 0.006 $\mu g/m^3$. The normal sampling period is 2 minutes; for concentrations of above 1 mg/m^3, the sampling period is 24 seconds, and a button allows the user to choose between 2-minute or 24-second sampling periods.

Sem, Tsurubayashi, and Homma (1977) conducted experiments with 11 piezobalances all connected to the same manifold source, and the instrumental concentrations were compared with measurements by a mass filter monitoring system. Over the concentration range of 0.3-3.0 mg/m^3, they report nearly all piezobalance concentrations within 10% of the filter-collected concentration. Since the two filter weights differed by as much as 4% and the filter flow meters had errors of $\pm$ 2%, they estimated that about half the 10% difference between filter and piezobalance was experimental error. In another series of experiments, they compared

piezobalance and low-volume filter measurements for 10 different aerosols. Over the range of 0.05-5.5 mg/m^3, piezobalance measurement of all tested aerosols except tobacco smoke were within $\pm$ 10% of the low-volume filter measurements. The instrument measured tobacco smoke about 15% lower than the low-volume filter. The piezobalance sensitivity values on these aerosols were generally within $\pm$ 10% of the value calculated by assuming ideal particle collection, deposition, and sensing. On nearly every 2-minute sample, the piezobalances repeated readings that were within 5% of each other. The authors conclude, "Thus, although somewhat greater accuracy can be obtained by calibration on the specific aerosol being measured, errors of no more than $\pm$ 15% and usually less than 10% are obtained on nearly all tested industrial smokes and dust (Sem, Tsurubayashi, and Homma, 1977, p. 584). They also compare the size distribution of the piezobalance with the American Conference of Governmental Industrial Hygienists (ACGIH) curve. The authors state that, since most natural and industrial aerosols have a broad size distribution and since spatial and temporal concentration variations generally exceed 10-20%, the error caused by the impactor's size distribution curve usually are insignificant. Other investigators have compared the performance of the piezobalance with filter collection devices (Ingebrethsen, *et al.*, 1988) and with other real-time monitors (Zhu, *et al.*, 1993).

The TSI Model 8510 piezobalance comes factory calibrated but its flow rate (1 liter/minute) must be checked periodically, and, after each usage, its crystal must be carefully cleaned with internal sponges using distilled water and a soap solvent supplied by the manufacturer. Also, its precipitator needle must be cleaned periodically with a solvent and compressed air. The frequency on the instrument's LED display indicates the status of the

crystal by showing its frequency, and a meter showing the operating voltage gives an indication of the status of the precipitator needle. With proper care and maintenance, the manufacturer states that the precision of each instrument should be $\pm$ 10 $\mu g/m^3$. In our own quality assurance evaluations, measurements of particle concentrations with two instruments carried side by side in several hundred stores, restaurants, and other outdoor locations showed that the average concentrations deviated by less than $\pm$ 10 $\mu g/m^3$.

Field Survey Methodology

Between May 17, 1992, and February 11, 1994, 26 visits were made on a variety of days of the week and times of day (usually in the late afternoon or evening) during the smoking period to measure concentrations and count smokers in the tavern. (As discussed later, a previous set of visits in 1979-80 had counted smokers without making measurements.) Without advance notice, the City of Menlo Park passed a regulation prohibiting smoking in all taverns within the city limits beginning on May 1, 1994. When the regulation went into effect and a "No Smoking" sign was posted at the tavern door, all smoking inside the tavern suddenly ceased. To determine the effect on indoor concentrations immediately after smoking ended, a set of 24 follow-up visits were made between May 17 and June 30, 1994 (first follow-up survey).

Because the first follow-up survey was conducted immediately after smoking was prohibited, it is unlikely that any other significant changes in tavern operation occurred (for example, changes in the ventilation system) during this six-week period. Comparing the concentrations on the 24 visits during first follow-up survey with the concentrations measured earlier on the 26 visits during the smoking period shows the immediate (short-term) change, if

any, in the indoor concentrations inside the tavern.

Because other factors (season, time of visit, etc.) could have affected the concentrations, a second set of 26 follow-up visits (second follow-up survey) were made later in the year (late summer, fall, and winter). These 26 follow-up visits sought to control for possible confounding factors (season, time of day, day of the week) by matching exactly the same day of the week, same time of day, and same visit duration in the same season as in the earlier 26 smoking visits. For example, an earlier smoking visit to the tavern on Thursday, 12/3/92, at 6:50 pm for 56 minutes found an indoor concentration that was 131 $\mu g/m^3$ above the outdoor concentration. A matched 56-minute nonsmoking follow-up measurement on Thursday, 12/2/94, at 6:50 pm was only 5.4 $\mu g/m^3$ above the outdoor concentration.

Figure 1 shows RSP measurements at three locations inside the tavern using two monitors on November 2, 1992. The outdoor readings from the two instruments ranged from 10 to 40 $\mu g/m^3$, with a mean of 18.3 $\mu g/m^3$ (average of 5 pairs of 2-minute observations), and the indoor concentrations ranged from 30 to 110 $\mu g/m^3$ (average of 28 pairs of 2-minute observations). From 8:05 pm to 8:55 pm, the two instruments the pairs of 2-minute averages agreed to within $\pm$ 5 $\mu g/m^3$. From 9:00 pm to 9:15 pm, one instrument was moved 15' away from the other, and the pairs of 2-minute averages still agreed to within $\pm$ 10 $\mu g/m^3$. Finally, from 9:20 pm to 9:40 pm, one instrument was moved 40' from the other, and the pairs of 2-minute averages agreed to within $\pm$ 20 $\mu g/m^3$. The most striking difference in Figure 1 is not between the pair of instruments indoors but between the concentrations observed inside the tavern and those observed outdoors before and after the visit: the indoor measurements were consistently higher than the outdoor measurements, which usually is the case.

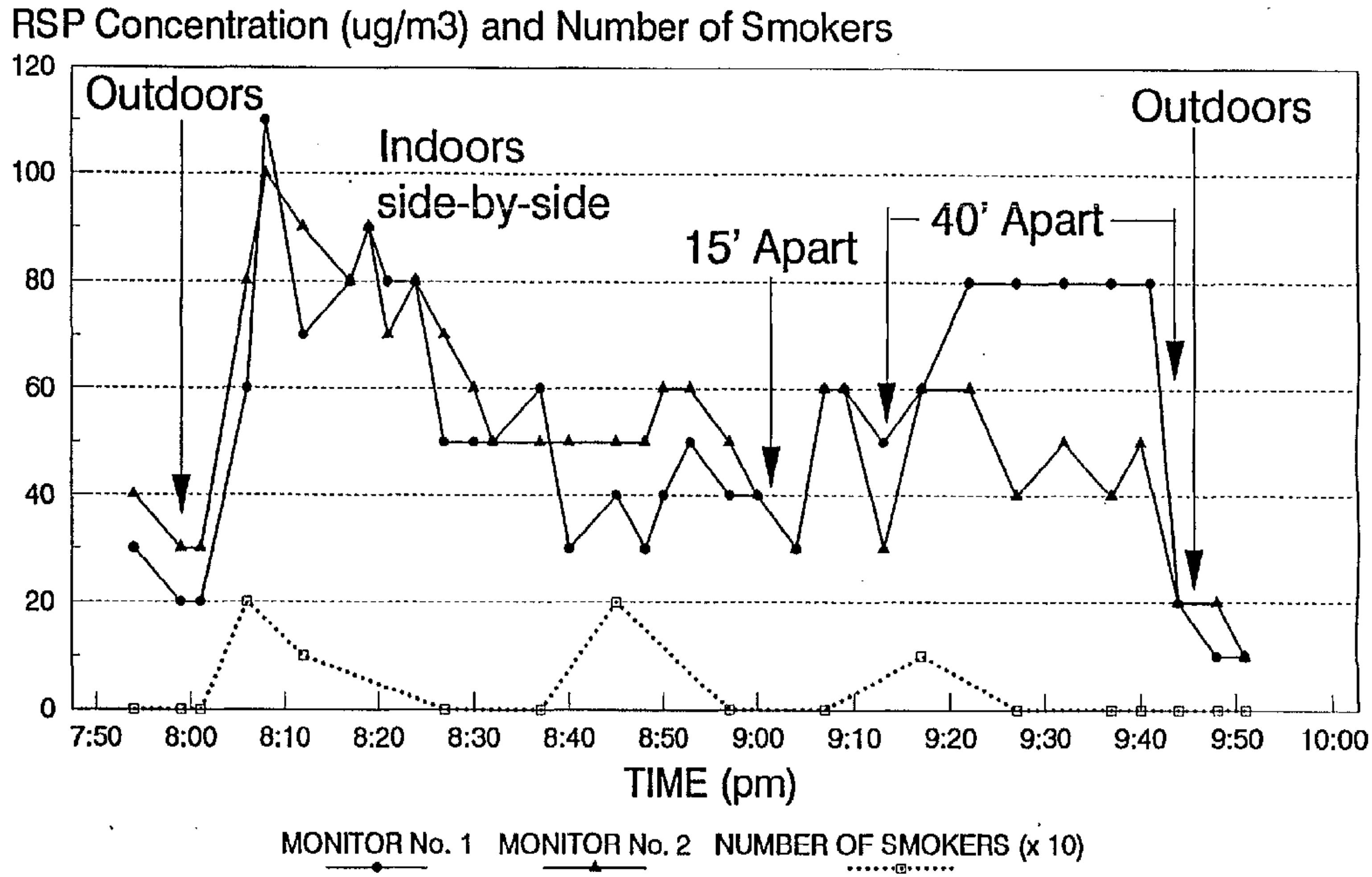

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Figure 1. Respirable suspended particle (RSP) concentration measured using two monitors during a visit to the tavern on 11/2/92.

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Figure 1 also shows the periodic counts of the number cigarettes inside the tavern that are being actively being smoked at any time t -- the active smoking count (ASC denoted as $n(t)$ in the modeling section). On this measurement visit, the ASC ranged from 0 to 2 cigarettes, with an average of 0.7 cigarettes. (Note that the ASC has been multiplied by 10 in this figure, so "20" on the figure is only 2 cigarettes). The average ASC may be viewed as an approximation of the average of the instantaneous time series of the counts of the number of persons who are actively smoking.

RESULTS

The results for the 26 visits during the two-year smoking period (Table 1) can be compared with the results for two follow-up studies: (a) 24 visits in May-June 1994 immediately after smoking was prohibited (Table 2); and (b) 26 additional visits in 1994-95 in the same seasons of the original visits but matched by time of day and day of the week (Table 3). This section compares the concentrations inside the tavern before and after smoking was prohibited. The next section evaluates a mathematical model designed to predict the concentrations from tobacco sources in the tavern.

Concentrations Observed Before and After Smoking was Prohibited

During the two-year smoking period (Table 1), the unadjusted average indoor RSP concentrations on 26 visits ranged from 26.3 $\mu g/m^3$ (August 6, 1992) to 181.8 $\mu g/m^3$ (January

Table 1. RSP Concentrations Measured in the Tavern Before Smoking Was Prohibited.									
Visit No.	Date	Day	Duration	Average Smoking Count	No. of Persons	Indoor RSP Mean (μg/m³)	Indoor RSP SD (μg/m³)	Outdoor RSP Mean (μg/m³)	I-O RSP Mean (μg/m³)
1	5/17/92	Sun	1 hr 5 min	1.7	21.0*	29.6	20.1	0.**	29.6
2	7/30/92	Thu	2 hr 2 min	1.8	25.3	56.9	43.3	18	38.9
3	8/6/92	Thu	42 min	1.0	22.2	26.3	11.7	16.7	9.6
4	10/30/92	Fri	2 hr	1.9	53.8*	180.5	56.7	32	148.5
5	11/2/92	Mon	1 hr 35 min	0.7	27.8	61.1	20.6	18.3	42.7
6	11/12/92	Thu	1 hr 6 min	1.9	60.4*	143.3	24.0	35	108.3
7	11/23/93	Tue	45 min	2.2	51.2*	127.1	24.4	26.7	100.4
8	12/3/92	Thu	56 min	1.5	56.0*	166.0	20.9	35	131.0
9	10/2/93	Sat	40 min	1.0	33.8	50.0	26.6	10	40.0
10	10/13/93	Wed	1 hr 13 min	0.6	50.0	38.1	9.8	10	28.1
11	10/15/93	Fri	1 hr 5 min	0.0	66.8*	25.3	6.4	14	11.3
12	10/20/93	Wed	42 min	1.8	36.0	127.7	33.2	17.5	110.2
13	10/21/93	Thu	1 hr 3 min	1.1	47.0*	67.6	21.1	22.5	45.1
14	11/5/93	Fri	59 min	1.0	86.8*	49.2	13.8	25	24.2
15	11/6/93	Sat	48 min	0.8	37.1	66.3	17.7	45	21.3
16	11/13/93	Sat	34 min	0.2	39.2	62.5	21.4	45	17.5
17	11/23/93	Tue	10 min	2.7	41.7*	152.0	29.5	27.5	124.5
18	12/4/93	Sat	13 min	0.5	35.0*	40.0	7.1	42	-2
19	12/20/93	Mon	1 hr 2 min	0.9	35.5*	159.5	39.8	35	124.5
20	1/11/94	Tue	53 min	0.0	32.8	53.0	14.5	30	23
21	1/22/94	Tue	35 min	1.7	38.5*	100.0	20.5	25	75
22	1/29/94	Sat	26 min	2.3	47.3*	181.8	67.1	66.7	115.1
23	2/2/94	Wed	38 min	1.0	37.0*	58.0	7.5	42.5	15.5
24	2/11/94	Fri	44 min	0.8	49.8*	53.8	15.6	10	39.8
25	2/16/94	Wed	28 min	0.2	13.6	30.0	19.0	15	15.0
26	2/21/94	Mon	32 min	1.1	12.3	52.2	16.4	14	38.2
			Mean:	1.17	40.7	83.0	--	26.1	56.8
			Std. Dev:		16.6	52.3	--	14.6	46.3

*Children were present. **Below detection limit. Notes: Tavern Area = 210 m²; Tavern Volume = 521 m³

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Table 2. First Follow-Up Survey of RSP Concentrations Measured in the Tavern Immediately After Smoking Was Prohibited on May 1, 1994: 24 Dates in the First Two Months After Prohibition								
Visit No.	Date	Day	Duration	No. of Persons	Indoor RSP (μg/m³)	Indoor RSP SD (μg/m³)	Outdoor RSP Mean (μg/m³)	I-O RSP Mean (μg/m³)
1	5/19/94	Thu	50 min	80.0*	7.4	9.3	0	7.4
2	5/31/94	Tue	35 min	50.3*	10.7	4.7	2.5	8.2
3	6/1/94	Wed	65 min	66.2*	10	0.0	10	0
4	6/2/94	Thu	30 min	51.0*	16	5.2	16	0
5	6/4/94	Sat	35 min	20.0*	8	6.3	10	-2
6	6/694	Mon	35 min	40.7*	23.1	9.5	6	17.1
7	6/8/94	Wed	33 min	39.5*	16.7	9.8	10	6.7
8	6/9/94	Thu	24 min	36	11.8	4.0	10	1.8
9	6/10/94	Fri	34 min	51	24.1	10.8	21.7	2.4
10	6/11/94	Sat	24 min	15.5*	12.5	4.6	20	-7.5
11	6/13/94	Mon	24 min	27	20	8.2	10	10
12	6/14/94	Tue	45 min	26.0*	10.5	2.4	5	5.5
13	6/16/94	Thu	41 min	41.0*	15.3	5.1	2.5	12.8
14	6/17/94	Fri	148 min	53.8	16.4	7.9	8	8.4
15	6/20/94	Mon	48 min	35.5*	10.6	2.4	8.6	2
16	6/22/94	Wed	30 min	75	18.5	3.8	5	13.5
17	6/23/94	Thu	45 min	37.5*	15.2	9.5	6.7	8.5
18	6/24/94	Fri	50 min	52.0*	12	4.1	10	2
19	6/25/94	Sat	43 min	17.5*	8.9	4.7	5.5	3.4
20	6/26/94	Sun	25 min	34.0*	11.8	7.5	5	6.8
21	6/27/94	Mon	38 min	23.7*	20	0.0	12	8
22	6/28/94	Tue	19 min	40.0*	13.8	5.2	15	-1.2
23	6/29/94	Wed	23 min	15.0*	27.8	9.7	10	17.8
24	6/30/94	Thu	32 min	70.5*	22.7	7.0	13.3	9.4
			Mean:	41.6	15.1	--	9.3	5.9
			Std. Dev:	18.5	5.5	--	5.3	6.1

*Children were present.

Notes: Tavern Area = 210 m²; Tavern Volume = 521 m³.

Table 3. Second Follow-Up Survey of RSP Concentrations Measured in the Tavern After Smoking was Prohibited: 26 Dates Matched by Season, Day of the Week, and Time of Day

Smoking Period							Nonsmoking Period -- Matched Visits					
Date	Day	Time	Duration of Visit	No. of Persons	No. of Smoker	I-O RSP ($\mu g/m^3$)	Date	No. of Persons	Indoor RSP Mean ($\mu g/m^3$)	Indoor RSP SD ($\mu g/m^3$)	Outdoor RSP Mean ($\mu g/m^3$)	I-O RSP ($\mu g/m^3$)
5/17/92	Sun	11:50 a	1 hr 5 min	21.0*	1.7	29.6	6/26/94**	34.0*	11.8	7.5	5.0	6.8
7/30/92	Thu	5:30 p	2 hr 2 min	25.3	1.8	38.9	8/18/94	23.8*	11.7	4.7	10.0	1.7
8/6/92	Thu	5:06 p	47 min	22.2	1.0	9.6	8/11/94	16.6*	4.0	5.0	2.0	2.0
10/30/92	Fri	8:02 p	2 hr	53.8*	1.9	148.8	10/28/94	59.9*	24.6	6.7	16.0	8.6
11/2/92	Mon	8:06 p	1 hr 35 min	27.8	0.73	42.7	11/7/94	36.0*	25.5	11.5	17.5	8.0
11/12/92	Thu	6:10 p	1 hr 6 min	60.4*	1.86	108.3	11/17/94	72.0	81.8	23.8	10.0	71.8
11/23/92	Mon	8:19 p	45 min	51.2*	2.2	100.4	11/21/94	18.0*	37.4	7.3	42.5	-5.1
12/3/92	Thu	6:50 p	56 min	56.0*	1.5	131.0	12/2/94	55.3	17.1	2.8	11.7	5.4
10/2/93	Sat	10:04 p	40 min	33.8	1.0	40.0	10/29/94	15.3	30.4	7.1	23.3	7.1
10/13/93	Wed	7:15 p	1 hr 13 min	50.0	0.56	28.1	11/9/94	48.3	25.4	7.8	6.7	18.7
10/15/93	Fri	7:59 p	1 hr 5 min	66.8*	0.11	11.3	11/4/94	73.0*	22.5	4.4	3.3	19.2
10/20/93	Wed	8:20 p	42 min	36.0	1.8	110.2	11/2/94	52.0	32.5	9.7	5.0	27.5
10/21/93	Thu	8:09 p.	1 hr 1 min	47.0*	1.1	45.1	11/3/94	58.7*	41.3	6.1	28.3	13.0
11/5/93	Fri	8:06 p	59 min	86.8*	1.0	24.2	11/11/94	76.5	57.1	9.0	47.1	10.0
11/6/93	Sat	8:04 p	48 min	37.1	0.8	21.3	11/12/94	78.8	82.0	24.8	66.7	15.3
11/13/93	Sat	10:46 p	34 min	39.2	0.2	17.5	11/19/94	18.0	45.7	9.4	52.0	-6.3
11/23/93	Tue	7:00 p	10 min	41.7*	2.67	124.5	11/8/94	31.0*	20.0	0.0	10.0	10.0
12/4/93	Sat	8:26 p	13 min	35.0*	0.5	-2.0	12/3/94	53.7*	35.7	15.1	11.3	24.4
12/20/93	Mon	8:02 p	1 hr 2 min	35.5*	0.88	124.5	11/14/94	31.0	60.4	11.6	48.3	12.1
1/11/94	Tue	8:00 p	53 min	32.8	0.0	23.0	1/17/95	39..8*	29.1	6.8	30.0	-0.9
1/22/94	Sat	6:20 p	35 min	38.5*	1..6	75.0	1/21/95	63.5*	58.6	6.6	20.0	38.6
1/29/94	Sat	10:30 p	26 min	47.3*	2.25	115.1	1/28/95	32.0*	45.0	23.2	38.0	7.0
2/2/94	Wed	8:07 p	38 min	37.0*	1.0	15.5	2/8/95	23.7*	36.4	10.1	26.6	9.8
2/11/94	Fri	6:31 p	44 min	49.8*	0.83	39.8	2/10/95	59.0*	28.5	6.7	25.0	3.5
2/16/94	Wed	12:06 p	28 min	13.6	0.20	15.0	2/15/95	19.0*	36.7	6.5	20.0	16.7
2/21/94	Mon	4:11 p	32 min	12.3	1.14	38.2	2/6/95	8.3	28.6	7.7	18.3	10.3
Mean			53 min	40.6	1.17	56.8	—	42.2	35.8	9.3	22.9	12.9
Std. Dev.			27.3 min	16.6	0.71	46.3	—	21.4	19.5	6.1	17.1	15.5

*Children were present; **Same day of week but different time of day.

Avg- 5 (4.8) people less with Non-Smok

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29, 1994), with an overall average of 83.0 $\mu g/m^3$ (SD = 52.3 $\mu g/m^3$)[1]. The average outdoor concentrations ranged from zero[2] (May 17, 1992) to 66.7 $\mu g/m^3$ (January 29, 1994) with an overall average of 26.1 $\mu g/m^3$ (SD = 14.6 $\mu g/m^3$)[1]. The average RSP concentration contributed by only those sources within the tavern was calculated to be 83.0 - 26.1 = 56.9 $\mu g/m^3$ (SE = $\pm$ 9.1 $\mu g/m^3$).

Calculating the I-O result by subtracting the outdoor concentration from the indoor concentration gives only an approximate estimate of the concentration contributed indoor sources (such as smoking, cooking, and resuspension of indoor dust); a more exact adjustment is described in the section on modeling. The indoor-minus-outdoor (I-O) adjusted concentrations for the 26 visits ranged from near zero (-2 $\mu g/m^3$ on December 4, 1993) to 148.5 $\mu g/m^3$ (October 30, 1992), with a mean of 56.8 $\mu g/m^3$ and a standard deviation of SD = 46.2 $\mu g/m^3$ (Table 1). The small negative value results from subtracting two similar values with experimental variability, the time lag due to indoor-outdoor infiltration, and the effect of the plating out of the infiltrated particles on surfaces (see modeling section). Allowing for round-off error, the average value of these 26 I-O indoor concentrations (56.8 $\mu g/m^3$) is approximately the same as the difference of between the average indoor and average outdoor concentrations (56.9 $\mu g/m^3$), as one would expect from the calculations in Table 1.

The I-O mean RSP concentration during the 26 smoking visits of 56.8 $\mu g/m^3$ was significantly higher than the corresponding I-O mean RSP concentration of 9.5 $\mu g/m^3$ observed on 50 nonsmoking visits for the two follow-up surveys combined. The histograms of RSP concentrations (Figure 2) showed a wider variation of interior RSP concentrations during the

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[1]SD denotes the standard deviation of the observed means on the 26 trips.

[2]A reading of zero should be interpreted as *less than the 5 $\mu g/m^3$* detection limit.

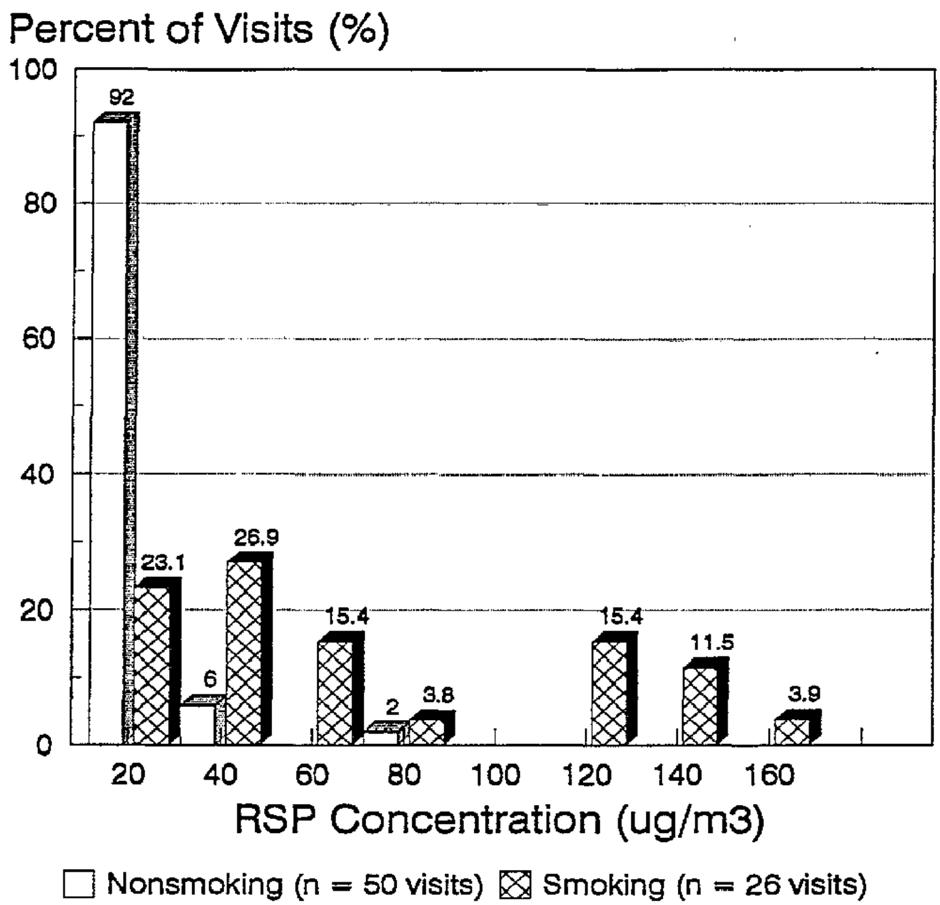

Figure 2. Histogram of interior (I-O) RSP concentration measured inside the tavern, comparing visits during the smoking period (crosshatched bars) with visits during both nonsmoking periods (light bars).

smoking period than during the nonsmoking period. During the smoking period, there were 6 visits (23.1 %) with average concentrations below 20 $\mu g/m^3$, but 8 visits (30.7 %) were above 100 $\mu g/m^3$. In contrast, 46 of the 50 nonsmoking visits (92 %) had average RSP concentrations below 20 $\mu g/m^3$. Of the four visits during the nonsmoking period with average I-O values above 20 $\mu g/m^3$, three were less than 40 $\mu g/m^3$ and the one high value (71.8 $\mu g/m^3$ on 11/17/94) could not be explained. No hidden smokers could be found on the premises either before or during the visit on that date, but 20 children were present at a tavern pizza party, and their activities (climbing about the tables and floor) may have stirred up particles on the tavern surfaces, raising resuspended dust concentrations. Except for this one high case, no other unusually high I-O RSP concentrations (above the 38.6 $\mu g/m^3$ reading on Saturday, 1/22/95) occurred during the 50 visits of both nonsmoking follow-up surveys.

The outdoor RSP concentration observed during the 24 visits of the first follow-up survey was 9.3 $\mu g/m^3$ (Table 2), which is lower than the outdoor RSP concentration of 26.1 $\mu g/m^3$ (Table 1) observed during the smoking visits. The lower outdoor concentrations occurred because ambient particle concentrations are low in May and June, when the first follow-up survey was conducted. The outdoor RSP concentration for the matched dates of the second follow-up survey was 22.9 $\mu g/m^3$, which is much closer to the outdoor concentrations in the fall-winter dates of the smoking period. Thus, the matched dates provide a better basis for comparing tavern concentrations before and after smoking, because matching reduces the effect of possible confounding factors (season, ambient levels, day of the week, time of day, tavern ventilation).

The average I-O tavern concentration observed during the matched set of nonsmoking visits was 12.9 $\mu g/m^3$, compared with 56.8 $\mu g/m^3$ for the smoking visits. This difference of 56.8 -

12.9 = 43.9 μg/m^3 is associated with the average active smoking count of 1.17 cigarettes. These findings -- based on the matched dates -- indicate that smoking contributed 77% of the total indoor RSP concentrations in the tavern, and the other RSP sources, such as cooking and resuspended dust, contributed 23%.

Tavern Attendance Before and After Smoking was Prohibited

The average attendance in the tavern during the smoking period was 40.6 persons (Table 1). In the six-week period immediately following smoking, the average attendance was 41.6 persons (Table 2), in the second follow-up survey, the average attendance also was 42.2 persons (Table 3). Although the attendance appeared to increase slightly after smoking was prohibited, these differences are not statistically significant. Thus, there was no decline in tavern attendance after the nonsmoking rule went into effect, and discussions with patrons suggested that many visitors were relieved by the "clean air." During the nonsmoking period, the smokers who visited the tavern briefly stepped outside the front door whenever they needed to smoke. Presumably, the new smoke-free environment attracted new nonsmoking customers who made up for lost patronage of smokers, if any.

This tavern has pinball machines and video games that are of interest to children. On 15 of the 26 visits during the smoking period and on 35 of the 50 visits during the nonsmoking periods, children were present, with very young children always accompanied by adults. Thus, children were present in the tavern on 50 of the total of 76 visits -- both during the smoking and nonsmoking conditions -- or 66% of the cases. The counts of tavern occupancy includes customers only, and, approximately 5 employees, on the average, were present on all visits, none

of whom smoked inside the premises. The tavern staff consisted of 18 employees, who rotated in 3 shifts, and 4 of these employees were smokers.

Historical Trends in Smoking Activity at this Tavern

Based on smoking habits, Repace (1980) hypothesized that about one-ninth (11.1 %) of the persons in public places were actively smoking at any instant of time, and Repace and Lowrey (1980) reported an average of 8.8% based on counts of smokers in a great variety of locations in 1979 in Washington, DC. Table 4 shows 20 separate visits between September 29, 1979, and February 20, 1980, to this same California tavern to test Repace's hypothesis by counting active smokers but not making any measurements. The active smoking count (ASC) ranged from 3 to 11 persons, with an average of 5.8 persons, and the overall attendance ranged from 47 to 103 persons, with an average of 66 persons. The proportion of the customers who were actively smoking in 1979-80 ranged from 6.3% to 14%, with an average of 8.8% -- identical to the value reported by Repace and Lowrey (1980).

In 1993-94, 20 follow-up visits were made to this tavern to determine how much the smoking activity had changed over the 14-year period -- matched to the earlier 1979-80 visits to control for the day of the week, the time of day, and the season (Table 4). Comparing active smoking on 20 matched visits in 1993-94 with those in 1979-80 shows that a significant decline in smoking activity occurred over the 14-year interval at this tavern. In contrast to the 1979-80 observed average ASC of 5.8 smokers, 1993-94 ASC ranged from 0 to 4 with an average of only

Table 4. Smoking Activity Counts in a Local Tavern Comparing 20 Visits at the Same Time and Same Day of the Week But Separated by 14 Years

1979-80						1993-94			
Date	Day	Time	No. of Smokers	No. of Persons	Percent %	Date	No. of Smokers	No. of Persons	Percent %
9/29/79	Sat.	10:15 pm	11	103	9.4	10/2/93	1	35	2.9
9/29/79	Sat.	10:25 pm	3	52	5.8	10/2/93	0	28	0
10/10/79	Wed.	7:45 pm	4	64	6.3	10/13/93	1	56	1.8
10/10/79	Wed.	8:45 pm	7	57	12.3	10/13/93	1	40	2.5
10/11/79	Thu.	8:55 pm	7	62	11.3	10/21/93*	0	41	0
10/11/79	Thu.	8:00 pm	9	65	13.8	10/21/93	0	72	0
10/17/79	Wed.	8:05 pm	5	90	5.6	10/20/93	2	40	5
10/20/79	Sat.	8:15 pm	5	64	7.8	11/6/93	1	37	2.7
11/5/79	Mon.	7:33 pm	6	78	7.7	11/29/93	4	33	12.1
11/20/79	Tue.	7:00 pm	7	50	14.0	11/23/93	2	43	4.7
11/24/79	Sat.	10:30 pm	7	53	13.2	1/29/94	2	42	4.8
12/1/79	Sat.	8:25 pm	4	47	8.5	12/4/93	0	35	0.0
12/17/79	Mon.	8:00 pm	5	82	5.9	12/20/93	0.9	36	2.5
1/15/80	Tue.	8:00 pm	5	67	7.5	1/11/93	0	22	0.0
1/20/80	Sat.	6:05 pm	4	65	6.2	1/22/94	2	28	7.1
1/20/80	Sat.	6:21 pm	7	73	9.6	1/22/94	3	36	8.3
2/6/80	Wed.	12:10 pm	3	48	6.3	2/16/94	1	13	7.6
2/6/80	Wed.	12:30 pm	7	97	7.2	2/16/94	0	14	0.0
2/9/80	Sat.	8:05 pm	6	57	10.5	2/19/94	3	40	7.5
2/18/80	Mon.	3:40 pm	4	53	7.5	2/21/94	2	14	14.3
Mean:			5.8	66.4	8.8%	-	1.3	35.3	4.2%

*Near match: same day of the week but not exactly the same time.

1.3 smokers, a decrease of 78%. However, the average number of patrons visiting the tavern declined by 47% over the same 14-year period, possibly due to the economic recession in California in the early 1990's, increased competition from other sports taverns; changes in lifestyle, or other factors. The data show that the proportion of the customers who were actively smoking decreased by 52% well before the nonsmoking regulation was passed. Thus, smoking activity decreased about one-half in the customer population, but, because patronage also dropped about one-half, the overall smoking activity in the tavern dropped to about one-quarter of its previous levels over the 14-year period. This sharp decline in smoking activity is consistent with beliefs often expressed by patrons of the tavern that smoking activity in public places has been declining rapidly in the San Francisco Bay area and throughout California.

MODELING CONCENTRATIONS IN THE TAVERN

Modeling concentrations in settings where people typically congregate is complicated by the difficulty of obtaining accurate information on all the variables (types of cigarettes smoked, air exchange rate, etc.) on particular visits. Nevertheless, it is important to determine how well the indoor modeling approaches can predict concentrations in this setting, because models offer a method for generalizing these findings to other locations and other situations. Measuring the air exchange rate was not possible when the tavern was crowded with customers, so special arrangements had to be made with the tavern management to visit during nonbusiness hours to measure the air exchange rate.

Cigarette Source Strengths

Many different methodologies -- such as chamber studies, measurements in microenvironments, personal monitoring surveys -- for determining the source strengths of cigarettes have been reported in the literature. Typical RSP emissions per cigarette reported in the literature are 11.4, 12.7, 12.9, 14.1, 14.4, 18, and 26 mg (Hildemann, Markowski, and Cass, 1991a, 1991 b; Koutrakis and Briggs, 1992; Leaderer and Hammond, 1991; Lofroth *et al.*, 1989; Nelson, Martin, Ogden, *et al.*, 1994; Ott, Langan, and Switzer, 1992; Ozkaynak, Xue, Weker, *et al.*, 1994; Pellizzari, Thomas, Clayton *et al.*; Repace, 1987; Repace and Lowrey, 1980; Repace and Lowrey, 1982; Rickert, 1984). Few studies have examined smoker emissions (sidestream plus exhaled mainstream smoke) in ordinary settings (taverns and restaurants) or the brand types likely to be found there.

Hildemann, Markowski, and Cass (1991a, 1991b) measured emissions of four different brands using a human smoker who sat beneath a hood that removed and collected the particles and smoke of four different brands. Hildemann (1994) found that the fine particle emissions from a Winston light cigarette was 14.1 mg, based on two 85 mm cigarettes that each lasted 8 minutes. The emissions from a Camel Regular cigarette was 21.84 mg, based on one 85 mm cigarette that lasted 9 minutes and another that lasted 6 minutes. The emissions from a 100 mm Benson and Hedges Menthol cigarette that lasted 12 minutes were 23.1 mg. Finally, the emissions from a Merit Filter Tip cigarette were 22.4 mg based on two cigarettes that each lasted 8 minutes. If we divide the total emissions by the smoking durations, these results give an RSP mean emission rate of 2.4 mg/min, with a minimum of 1.8 mg/min and a maximum of 2.8 mg/min for the various brands and cigarette types tested. These authors' research is one of the few information sources

available for the average emission rate, rather than the total number of mg emitted by the cigarette or the emissions per unit length burned of the cigarette. The latter values, by themselves, do not permit emission rates to be calculated, because emission rates depend on the rates at which people smoke their cigarettes in realistic settings. Their range of total emissions (14.1 to 22.4 mg) is consistent with the range reported elsewhere in the literature.

Air Exchange Rate

To measure the air exchange rate without interfering the occupants of the tavern, a special arrangement was made with the tavern management to visit during nonbusiness hours and to measure the air exchange rate using a tracer technique. The owners adjusted the cooking grill ventilation system, doors, and windows to "typical" conditions. Three Langan L15 carbon monoxide (CO) monitors (Langan, 1992) were used to measure and record CO concentrations at 10-second intervals at three widely-spaced locations in the tavern. At two of these locations, RSP was monitored over 2-minute averages using a pair of TSI Model 8510 piezobalances. As described by Ott, Langan, and Switzer (1992), the time series of the concentration decay curves from these two pollutants allows one to determine both the ventilatory air exchange rate ϕ_v and the effective air exchange rate for particles ϕ_p. The difference between these two rates, $\phi_d = \phi_p - \phi_v$, is due to the deposition of particles on indoor surfaces. The northwest corner booth and the southwest corner booths were approximately 36' (11 m) from each other, and the central table sampling location was 21' (6.4 m) from the northwest corner booth and 20' (6.1 m) from the southwest corner booth.

To create a strong source of CO and particles for the indoor tracer experiment, four cigars

were smoked in the center of the tavern, two at a time. The characteristic CO decay pattern was very similar at all three locations (Figure 3), suggesting that air in the tavern is fairly well-mixed. The units are listed in parts-per-ten-million (pptm), so 10 pptm = 1 ppm. Using a Langan DataBear™, readings were logged at 10-second intervals, giving 360 data points (small circles and squares on the figure) per hour. A semi-logarithmic plot of the CO concentration time series (logarithm of CO concentration versus time) yields relatively straight lines for all three locations (Figure 4). A straight line on semi-logarithmic paper indicates that all three locations follow the exponential solution to the mass-balance equation. The similarity of slopes indicates that the ventilatory air exchange rates calculated from any of these three locations are almost the same, regardless of the location, or $\phi_v = 7.5$ ach. Thus, a volume of air equal to that of the tavern ($521 m^3$) is replaced every $60/\phi_v = 8$ minutes.

The RSP concentration time series after the four cigars were smoked shows a similar decay pattern at two locations, the central table and the southwest corner booth (Figure 5). After subtracting the background RSP concentration ($20\ \mu g/m^3$) and taking logarithms to fit the exponential function, the slope of RSP decay time series gave an effective air exchange rate for particles of $\phi_p = 7.63$ ach. The closeness between the ventilatory and particle air exchange rates in this tavern may be due partly to the high overall air exchange rate of the tavern, since high air flow rates may reduce the time available for the particles to deposit on surfaces.

Modeling Indoor Concentrations

The simplest indoor air model for cigarettes is one based on the *average concentration* x_{avg}

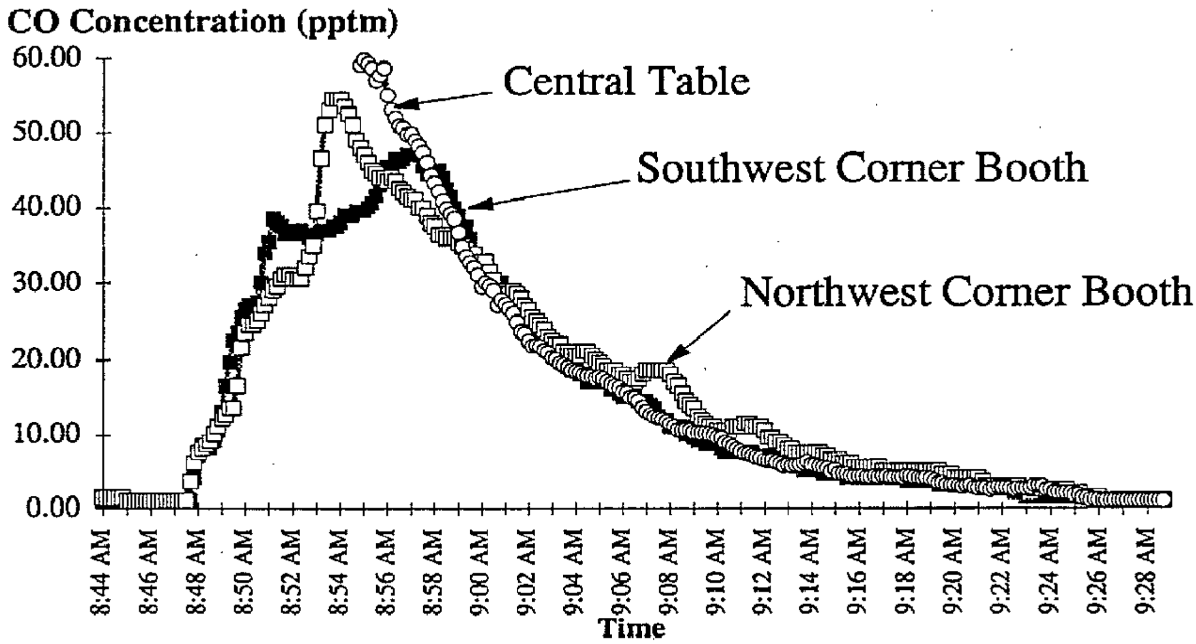

Figure 3. CO concentration time series measured in the tavern at three locations after four cigars were smoked.

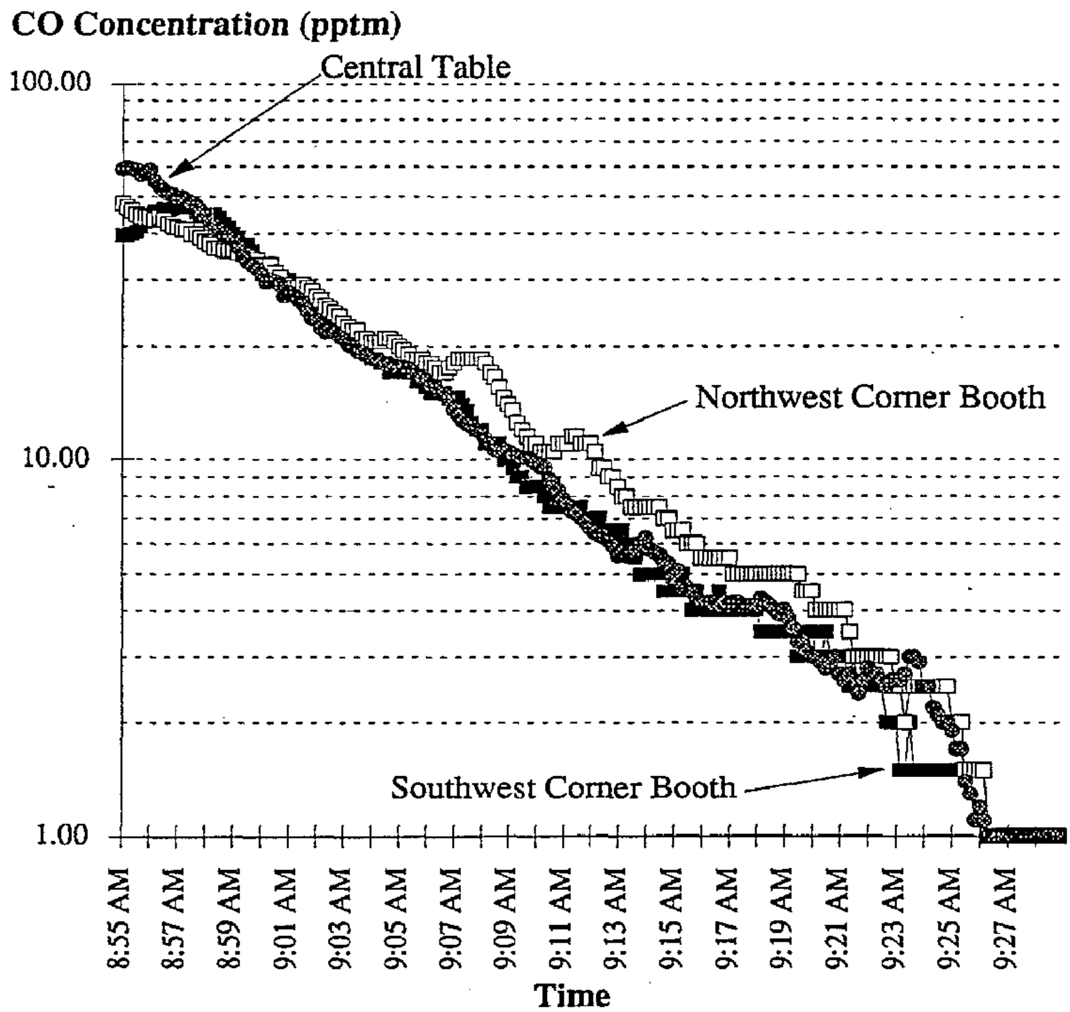

Figure 4. Semi-logarithmic plot of CO concentration measured in the tavern at three locations after four cigars were smoked.

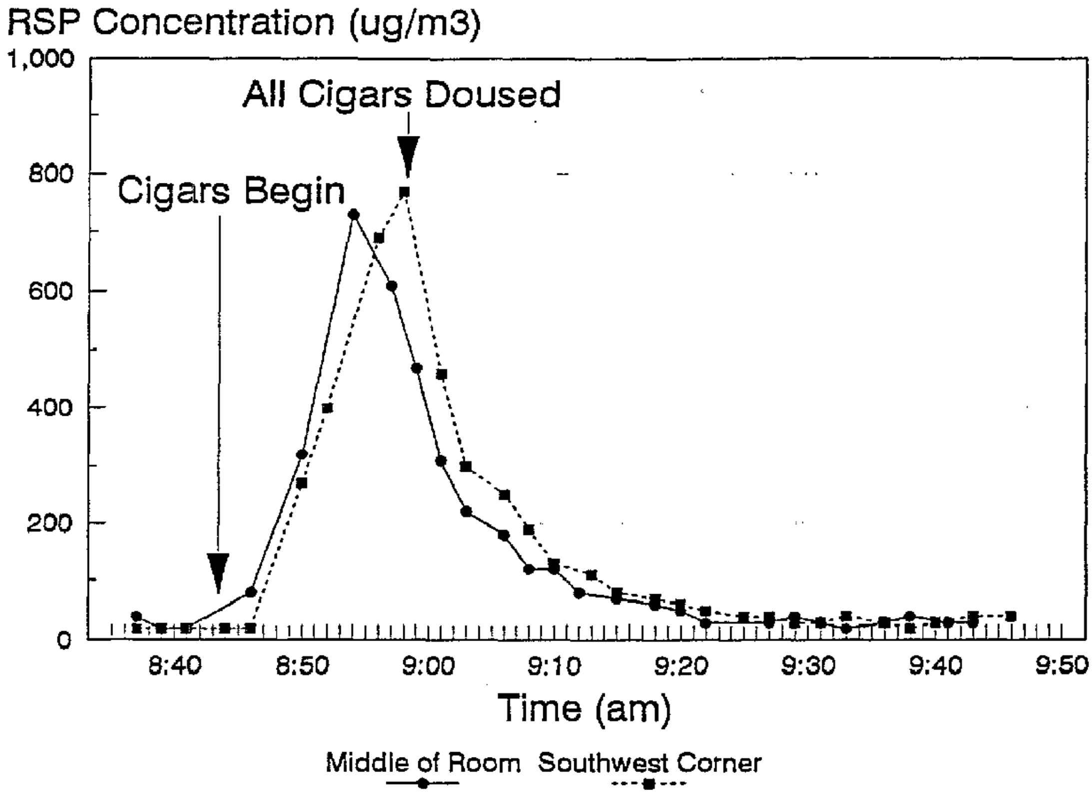

Figure 5. Respirable suspended particle (RSP) concentration measured in the tavern after smoking four cigars.

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over all visits, the *average active smoking count* n_{ave} over all visits, the average cigarette emission rate g_c, the effective air exchange rate ϕ_p, and mixing volume v (Ott, Langan, and Switzer, 1992):

$$x_{ave} = \frac{n_{ave}\, g_c}{\phi_p v} \qquad (1)$$

Applying this equation to the tavern, we obtain x_{ave} = (1.17 cigarettes)(2.4 mg/min)(60 min/hr)(1000 μg/mg)/(7.6 ach)(521 m^3) = 42.5 μg/m^3. Here, x_{ave} may be viewed as the expected value of the indoor concentration contributed by smoking with n_{ave} as the expected value of the number of active smokers. The expected concentration predicted by the model is very close to the concentration obtained by subtracting the average observed I-O concentration for the matched nonsmoking dates from the average observed I-O concentration during the smoking dates, or 56.8 μg/m^3 - 12.9 μg/m^3 = 43.9 μg/m^3. This subtraction deducts the average concentration believed to be caused by cooking and resuspended dust during the smoking period and it corresponds to the average smoking count of n_{ave} = 1.17, or 37.5 μg/m^3 per cigarette. If we use the lowest emission rate (1.8 mg/min) and the highest emission rate (2.8 mg/min) from Hildemann (1994), then the average incremental RSP concentration predicted by Equation 1 from smoking in the tavern ranges from 31.9 μg/m^3 to 49.6 μg/m^3. The incremental average RSP concentration of 43.9 μg/m^3 observed in the tavern lies well within this predicted range. The model in Equation 1 predicts an average RSP concentration of x_{ave} = 42.5/1.17 = 36.3 μg/m^3 per cigarette in this tavern.

How well do the average concentrations on *individual visits* agree with the concentrations predicted by an indoor air quality model? Ott, Langan, and Switzer (1992) derive the general mass balance equation for particles in an indoor setting as follows:

$$\frac{1}{\phi_p}\frac{dx(t)}{dt} + x(t) = \frac{p\phi_v}{\phi_p}x_o(t) + \frac{g(t)}{v\phi_p} \qquad (2)$$

where $x(t)$ = concentration in indoor setting as a function of time $[M/L^3]$

$x_o(t)$ = outdoor concentration entering the microenvironment $[M/L^3]$

$g(t)$ = emission rate of sources inside tavern $[M/T]$

ϕ_p = effective air exchange rate for particles $[1/T]$

ϕ_v = ventilatory air exchange rate $[1/T]$

p = dimensionless penetration factor

v = volume of the microenvironment $[L^3]$

As discussed earlier, the effective air exchange rate for RSP is the sum of the ventilatory air exchange rate and the incremental air exchange rate due to the deposition of particles on surfaces, or, $\phi_p = \phi_v + \phi_d$.

Typical sources of RSP are cigarettes, cooking, and resuspended dust caused by mechanical agitation from the activities of tavern occupants (Repace and Lowrey, 1980). Following the approach of Klepeis *et al.* (1995), we assume that the instantaneous cigarette source emission rate is proportional to the product of the average source emissions per cigarette g_c multiplied times the number of cigarettes being actively smoked as a function of time, or $n(t)g_c$. Thus, the total indoor source emission rate is represented by

$$g(t) = n(t)g_c + g_{cook}(t) + g_{dust}(t) \qquad (3)$$

When smoking is prohibited, we set $n(t) = 0$, because only the cooking source $g_{cook}(t)$ and the resuspended dust source emission rate $g_{dust}(t)$ remain in this equation.

Each RSP measurement from a visit to the tavern (Tables 1, 2, and 3) is the *average concentration* over the entire visit $\bar{x}$, which was computed by averaging the RSP concentration time series over the visit, which lasted from 10 to 122 minutes (Table 1). Because of the

importance of averages, it is useful to derive from the model an expression for the average concentration on each visit. If T denotes the duration of the visit, then the average concentration inside the microenvironment between time periods t and $t + T$ is:

$$\bar{x} = \frac{1}{T}\int_{t}^{t+T} x(t)dt \qquad (4)$$

If we integrate each term in Equation 1 and divide by the averaging period T, we obtain:

$$\frac{1}{T\phi_p}[x(t+T) - x(t)] + \frac{1}{T}\int_{t}^{t+T} x(t)dt = \frac{\phi_v p}{\phi_p T}\int_{t}^{t+T} x_o(t)dt + \frac{1}{T}\int_{t}^{t+T} \frac{g(t)}{v\phi_p} \qquad (5)$$

The left-hand side of this equation consists of two terms: $[x(t+T) - x(t)]/T\phi_p = \Delta x/T\phi_p$ and the average concentration during the visit $\bar{x}$. The right-hand side consists of two terms: the outdoor average concentration $\bar{x}_o$ weighted by the factor $p\phi_v/\phi_p$ and the average source strength $\bar{g}$ weighted by the factor $1/(v\phi_p)$. Thus, Equation 5 can be written in terms of the averages $\bar{x}$, $\bar{x}_o$, and $\bar{g}$:

$$\frac{\Delta x}{T\phi_p} + \bar{x} = \frac{p\phi_v}{\phi_p}\bar{x}_o + \frac{1}{v\phi_p}\bar{g} \qquad (6)$$

The first term of the left side of this equation $\Delta x/T\phi_p$ is a "trend correction term," because it corrects for changes in the initial concentration at the beginning of the visit and the final concentration observed at the end of the visit. If the initial and final concentrations were the same, then $\Delta x = 0$, and this term would disappear. Notice that the change in concentration Δx is divided by the product of T and ϕ_p, indicating that this term approaches zero if the product of the visit duration T and the effective air exchange rate ϕ_p becomes large relative to the change in concentration over the visit Δx. If the concentration increases during the visit ($\Delta x > 0$), then the observed average concentration $\bar{x}$ will be smaller than the concentration predicted from the average source term $\bar{g}$ and the concentration $\bar{x}_o$ infiltrating from outdoors, because the observed

indoor concentration "lags behind" the source change and needs to "catch up" in time. The trend correction term $\Delta x/T\phi_p$ introduced in this paper is exact and is important for predicting concentrations from source emission rates in other indoor locations. This trend correction term also is useful for designing indoor air field studies, because making the product $T\phi_p$ large relative to Δx minimizes the need for trend correction on a visit and simplifies the analysis. If the initial and final concentration is observed to differ on a particular visit, then making the visit duration T longer helps reduce the need for a trend correction.

The first term on the right side of Equation 6 adjusts for absorption of outdoor particles as they infiltrate indoors. The penetration of particles into the tavern from outdoors is represented by the dimensionless penetration factor p, and the deposition of these particles on surfaces is reflected by the ratio ϕ_v/ϕ_p. Thus, the outdoor concentration $\bar{x}_o$ is "weighted" by the factor $p\phi_v/\phi_p$ when it becomes the indoor concentration.

From the instantaneous sources in Equation 5, the average source strength $\bar{g}$ is written as the sum of the average source strengths from smoking, cooking, and resuspended dust:

$$\bar{g} = \bar{n}g_c + \overline{g_{cook}} + \overline{g_{dust}} \tag{7}$$

Substituting Equation 7 for $\bar{g}$ into Equation 6 and rearranging terms allows the average concentration inside the tavern as to be written as a linear regression equation:

$$y = m\bar{n} + b \tag{8}$$

where $y = \bar{x} + \Delta x/T\phi_p - x_o(p\phi_v/\phi_p)$

$m = g_c/v\phi_p$

$\bar{n}$ = average active smoking count (ASC) during the visit

$b = \bar{g}_{cook}/v\phi_p + \bar{g}_{dust}/v\phi_p$

To illustrate the application of Equation 8 to the experimental data, consider the visit on Monday, 2/21/94, which lasted 32 minutes (Table 1). Although not shown in the table, the beginning

instantaneous RSP concentration for this visit was 50 $\mu g/m^3$ and the ending concentration was 30 $\mu g/m^3$, so $\Delta x = 30 - 50 = -20\ \mu g/m^3$. We compute $\Delta x/(T\phi_p) = (-20\ \mu g/m^3)/[(32\ \text{minutes})(7.63\ \text{ach})(1\ \text{hour}/60\ \text{minutes})] = -4.9\ \mu g/m^3$. Next, we compute the outdoor RSP concentration assumed to be present indoors as $x_o(p\phi_v/\phi_p) = (14\ \mu g/m^3)(1)(7.5\ \text{ach}/7.63\ \text{ach}) = 13.8\ \mu g/m^3$. Using the observed indoor concentration of $x = 52.2\ \mu g/m^3$ for an ASC of $\bar{n} = 1.1$ cigarettes, we compute:

$$y = 52.2 - 4.9 - 13.8 = 33.5\ \mu g/m^3 \tag{9}$$

Here, y is the observed indoor average concentration corrected both for the trend during the visit and for the concentration infiltrating from outdoors. Because the initial RSP concentration at the beginning of each visit and the final RSP concentration at the end of the visit both are available from our data, it was possible to calculate Δx for each visit to the tavern.

Using the effective air exchange rage ($\phi_p = 7.63$ ach) measured in this tavern during the experiment when patrons were not present (fans and doors were adjusted by the management to reflect "typical" conditions), it was possible to calculate the trend adjustment term $\Delta x/(\phi_p T)$. This adjustment ranged from $-39.4\ \mu g/m^3$ to $+27.2\ \mu g/m^3$ for the 26 smoking visits, with a mean of $-1.3\ \mu g/m^3$ (SD = $11.9\ \mu g/m^3$), which is close to zero. Expressed as a percentage of the observed indoor concentration, this trend correction term ranged from -47% to +45%, with an average of -2.0% (SD = 16.2%). Because the trend adjustment term, averaged over all 26 smoking visits, is almost zero, the trend adjustment procedure has little effect on the overall *average* concentration x_{ave} predicted by Equation 1.

Equation 8 also includes the term $x_o p(\phi_v/\phi_p)$, which accounts for the concentration contributed by outdoor air infiltrating into the tavern. Using analyses from the Particle Total Exposure Assessment Methodology (PTEAM) study, Wallace (1994) concludes that $p = 1$, primarily because fine particles are small enough to penetrate walls and cracks like a gas. Using the ventilatory and particle air exchange rates measured in this tavern, this infiltration factor is computed as $p(\phi_v/\phi_p) = (1)(7.5/7.63) = 0.983$. Thus, the simple process of subtracting the outdoor from the indoor concentration to give the concentration contributed by indoor sources (that is, the I-O approximation described earlier) gives a fairly accurate estimate for this tavern, because the

adjusted infiltrated concentration for this tavern is 98.3% of the outdoor value, an error of only 1.7% The regression analysis based on Equation 8 uses the exact values (Figure 6).

The resulting scatter plot for all smoking and matched nonsmoking visits in Figure 6 shows variability that probably results from differences in air exchange rates on different dates. In this regression analysis, the slope is the average cigarette source strength g_{c}, and the y-intercept is the average RSP concentration contributed by all sources other than cigarettes (for example, cooking and resuspended dust). For the 26 smoking visits only, $R^2 = 0.51$; for the combined total of 52 smoking and matched nonsmoking visits, $R^2 = 0.59$, with a y-intercept of 9.8 $\mu g/m^3$ and a slope of 40.4 $\mu g/m^3$ per cigarette. Despite our lack of knowledge of the air exchange rates on the dates, this result indicates that the active smoking count explains more than 50% of the variability in the RSP concentrations observed on individual visits. This result for the slope is close to the observed average concentration of $(43.9/1.17) = 37.5$ $\mu g/m^3$ per cigarette discussed earlier in connection with Equation 1. The y-intercept of 9.8 $\mu g/m^3$ is an estimate of the indoor RSP concentration contributed by cooking and resuspended dust, since it is the value of the regression line at which the smoking count is zero. From the regression results, the average smoking count of 1.17 cigarettes gives an RSP concentration of $(1.17)(40.4) = 47.3$ $\mu g/m^3$, which implies that ETS contributes $(47.3)/(47.3 + 9.8) = 83\%$ to the RSP concentrations in this tavern. This result is not too different from the 77% obtained using the less precise I-O estimates in Tables 1-3.

SUMMARY AND CONCLUSIONS

This research has taken advantage of an opportunity created by local government to conduct a unique natural experiment: comparison of concentrations inside a sports tavern before and after smoking was prohibited. The resulting data show that, even though smoking rates were low at the time of the nonsmoking regulation, RSP concentrations measured inside the tavern decreased considerably after prohibition of smoking.

During 26 visits over a two-year period during which smoking was allowed, the average indoor RSP concentration was 56.9 $\mu g/m^3$ higher than the outdoor concentrations. RSP average concentrations measured on 24 visits immediately after smoking ended dropped to only 5.9 $\mu g/m^3$ above the outdoor levels, a decrease of 90%. A second follow-up survey on 26 matched dates

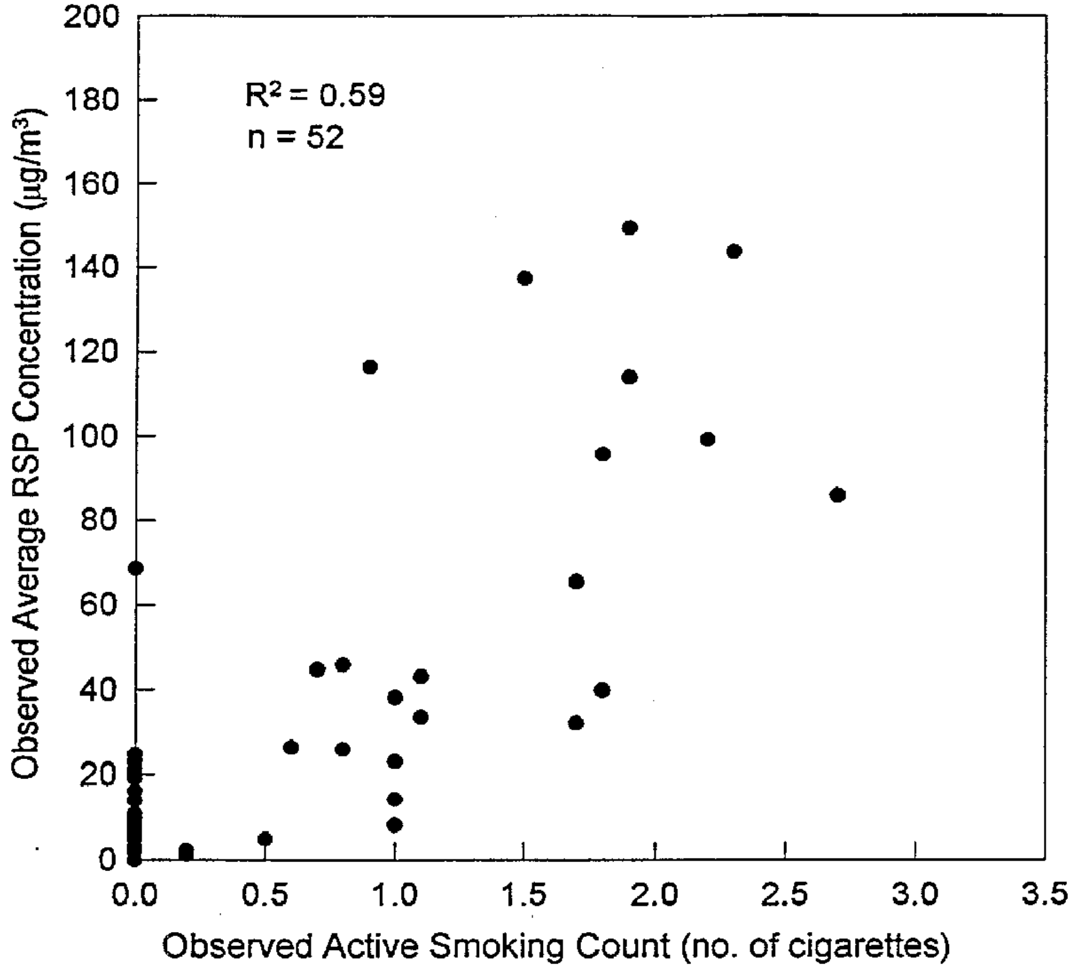

Figure 6. Scatter plot showing the average RSP concentration attributable to smoking versus average active smoking count on 52 visits, combining the smoking and matched nonsmoking periods.

to control for the season, time of day, and day of the week, found indoor concentrations that were 12.9 $\mu g/m^3$ above the outdoor levels. Using an analysis based on matched dates, smoking contributed about 77% of the observed indoor RSP concentrations, with other sources contributing 23%. Incorporating an adjustment into the analysis that takes into account concentration trends that occurred during each visit and modifying the outdoor concentration infiltrating indoors to include particle deposition, the regression analysis gives a similar result: 83% of the indoor RSP concentrations come from smoking and 17% from other sources, such as cooking and resuspended dust.

Wide variation in RSP concentrations occurred on visits during the smoking period, with I-O concentrations ranging from 9.6 $\mu g/m^3$ to 148.8 $\mu g/m^3$. During the smoking period, 30% of the visits were above 100 $\mu g/m^3$ and only 23% were below 20 $\mu g/m^3$. In contrast, during the nonsmoking periods, 93% of the 43 visits (both follow-up studies combined) were below 20 $\mu g/m^3$, and no visit was above 100 $\mu g/m^3$.

Using the cigarette emission rate of 2.4 mg/min from the literature, the observed average active smoking count of 1.17 cigarettes, and the tavern volume of 521 m^3, a mathematical model based on the mass balance equation predicted an RSP concentration of 42.5 $\mu g/m^3$, which agreed well with observed average RSP concentration of 43.9 $\mu g/m^3$. The model predicts that the average RSP concentration in the tavern will increase by $(1.0/1.17)(42.5) = 36$ $\mu g/m^3$ for each additional cigarette. If the active cigarette count n_{ave}, the volume v, or the air exchange rate ϕ_p were different, then we would use the formula $(n_{ave})(2.4\ \text{mg/min})/(\phi_p v)$ to calculate the expected value of the RSP concentration from smoking.

Predicting the concentrations in the tavern on individual dates requires the air exchange rate on each date. Using a single air exchange rate measured in the tavern on one occasion to compute concentrations for 52 visits yielded regression results with $R^2 = 0.59$, which indicates that, even without date-specific air exchange rates, the average smoking count $\bar{n}$ on different explains more than 50% of the variation in the observed RSP concentrations. This finding suggests that variation in the air exchange rate is not as important as other factors.

Over the last 14 years, smoking activity declined at this tavern by 78% before any nonsmoking regulation was passed. Part of this decrease was due to the 52% decrease in smoking activity per person, but and part of it was due to a 47% decrease in patronage. (The patronage

does not include the average count of five employees present on all visits.) If the active smoking count of 5.8 cigarettes observed in 1979-80 is used for n_{ave}, then the model predicts that the incremental average RSP concentration due to smoking of 210 $\mu g/m^3$. This estimate is similar to the RSP concentrations measured in taverns and restaurants by Repace and Lowrey (1980) more than a decade ago. For example, they measured 526 $\mu g/m^3$ in a 507 m^3 bar and grill in Washington, DC, with an active smoking count of 9 cigarettes, and they estimated air exchange rates ranging from 1.3 ach to 13.4 ach. Our model would predict this same concentration for an air exchange rate of $\phi_p = 4.7$ ach instead of 7.63 ach.

This research has sought to contribute insights to the modeling indoor RSP concentrations from smoking by testing a model under realistic conditions in a sports tavern. The model performed well and may be applicable to other similar taverns where smoking is allowed. The study indicates that this particular tavern has benefitted from the nonsmoking policy imposed upon it by the city. Not only did RSP concentrations decline considerably when the nonsmoking policy was implemented, but the two follow-up surveys show there was no decline in customer attendance.

DISCLAIMER

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